

観測水面形を用いた小規模河床形態発生時の流量・粗度係数・河床位・流砂量の推定

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1. はじめに

洪水時の水位、流量、抵抗特性、河床位、流砂量の時空間変化等を総合的に把握することは、河道の維持管理を行う上で不可欠である¹⁾。小規模河床形態の発生は、洪水時の抵抗を変化させることから、その変化の把握は極めて重要である。本研究は、以上のような背景を踏まえ、小規模河床形態の実験結果に基づき水面形の経時変化を与条件とした流量・粗度係数・河床位・流砂量の時空間推定法の予測精度について検討したものである。

2. 水面形の経時変化に基づく流量・粗度係数・河床位・流砂量の推定法の概要

本推定法は、常流を対象に、水面形と上下流端での河床位の経時変化を与条件として、1次元浅水流方程式と流砂の連続の式に基づき、流量・粗度係数・河床位の時空間分布を推定する手法である。基礎方程式は、式(1)の1次元浅水流方程式と式(2)の流砂の連続の式¹⁾である。式(1)の離散化には流束差分法を用い、発生・消滅ベクトル $\mathbf{S}$ については特性速度で風上化を行った。式(2)の離散化には風上差分を用いた。

$$\begin{aligned} \frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \mathbf{S} &= \mathbf{0}; \mathbf{U} = (A \quad Q)^T; \mathbf{E} = (Q \quad Q^2/A + gI)^T; \mathbf{S} = (0 \quad gI_2 + gA(S_0 - S_f))^T \cdots (1) \\ \frac{\partial z_b}{\partial t} + \frac{1}{\rho} \left\{ (1-p)B_s \right\} \cdot \frac{\partial Q_B}{\partial x} &= 0 \cdots (2) \quad \mathbf{U}^{t+\Delta t} = \mathbf{U}_i^t - \Delta t / \Delta x [\delta \mathbf{E}_{i+1/2}^t + \delta \mathbf{E}_{i-1/2}^t] \cdots (3) \\ \delta \mathbf{E}_{i+1/2}^t &= \sum_{j=1}^2 \left\{ [1 \pm \operatorname{sgn}(\tilde{\lambda}^j)] / 2 (\lambda^j \tilde{\alpha}^j - \tilde{\beta}^j) e^j \right\}; \operatorname{sgn}(a) = \begin{cases} 1 & a > 0 \\ -1 & a \leq 0 \end{cases} \quad \tilde{\alpha}^1 = (\tilde{\lambda}^1 \Delta A - \delta Q) / 2 \tilde{c}; \tilde{\alpha}^2 = -(\tilde{\lambda}^2 \Delta A + \delta Q) / 2 \tilde{c}; \tilde{\beta}^1 = -S_2 / 2 \tilde{c}; \tilde{\beta}^2 = -\beta^1 \\ \tilde{c}_{i-1/2} \Delta n_{i-1/2}^t - \tilde{c}_{i+1/2} \Delta n_{i+1/2}^t &= \tilde{D}_i; \tilde{c}_{i+1/2} = -(g \tilde{A}_{i+1/2} \tilde{u}_{i+1/2} / R_{i+1/2}^{4/3}) \cdots (4) \quad n_{i+1/2}^{t+\Delta t} = n_{i+1/2}^{t-\Delta t} + \Delta n_{i+1/2}^t \cdots (5) \\ \tilde{D}_i &= (A_{i+1/2}^{t+\Delta t} - A_i^t) / \Delta t + \frac{1}{\Delta x} \left\{ \tilde{A}_{i+1/2}^1 \tilde{u}_{i+1/2}^1 + \tilde{A}_{i+1/2}^2 \tilde{u}_{i+1/2}^2 - \frac{g \tilde{A}_{i+1/2}}{2 \tilde{c}_{i+1/2}} \left\{ \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i+1} - A_i) / B_{i+1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_i - A_{i-1}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-1} - A_{i-2}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-2} - A_{i-3}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-3} - A_{i-4}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-4} - A_{i-5}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-5} - A_{i-6}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-6} - A_{i-7}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-7} - A_{i-8}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-8} - A_{i-9}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-9} - A_{i-10}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-10} - A_{i-11}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-11} - A_{i-12}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-12} - A_{i-13}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-13} - A_{i-14}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-14} - A_{i-15}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-15} - A_{i-16}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-16} - A_{i-17}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-17} - A_{i-18}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-18} - A_{i-19}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-19} - A_{i-20}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-20} - A_{i-21}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-21} - A_{i-22}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-22} - A_{i-23}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-23} - A_{i-24}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-24} - A_{i-25}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-25} - A_{i-26}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-26} - A_{i-27}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-27} - A_{i-28}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-28} - A_{i-29}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-29} - A_{i-30}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-30} - A_{i-31}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-31} - A_{i-32}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-32} - A_{i-33}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-33} - A_{i-34}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-34} - A_{i-35}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-35} - A_{i-36}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-36} - A_{i-37}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-37} - A_{i-38}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-38} - A_{i-39}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-39} - A_{i-40}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-40} - A_{i-41}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-41} - A_{i-42}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-42} - A_{i-43}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-43} - A_{i-44}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-44} - A_{i-45}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-45} - A_{i-46}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-46} - A_{i-47}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-47} - A_{i-48}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-48} - A_{i-49}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-49} - A_{i-50}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-50} - A_{i-51}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-51} - A_{i-52}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-52} - A_{i-53}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-53} - A_{i-54}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-54} - A_{i-55}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-55} - A_{i-56}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-56} - A_{i-57}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-57} - A_{i-58}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-58} - A_{i-59}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-59} - A_{i-60}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-60} - A_{i-61}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-61} - A_{i-62}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-62} - A_{i-63}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-63} - A_{i-64}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-64} - A_{i-65}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-65} - A_{i-66}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-66} - A_{i-67}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-67} - A_{i-68}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-68} - A_{i-69}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-69} - A_{i-70}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-70} - A_{i-71}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-71} - A_{i-72}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-72} - A_{i-73}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-73} - A_{i-74}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-74} - A_{i-75}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-75} - A_{i-76}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-76} - A_{i-77}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-77} - A_{i-78}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-78} - A_{i-79}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-79} - A_{i-80}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-80} - A_{i-81}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-81} - A_{i-82}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-82} - A_{i-83}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-83} - A_{i-84}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-84} - A_{i-85}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-85} - A_{i-86}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-86} - A_{i-87}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-87} - A_{i-88}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-88} - A_{i-89}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-89} - A_{i-90}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-90} - A_{i-91}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-91} - A_{i-92}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-92} - A_{i-93}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-93} - A_{i-94}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-94} - A_{i-95}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-95} - A_{i-96}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-96} - A_{i-97}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-97} - A_{i-98}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-98} - A_{i-99}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-99} - A_{i-100}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-100} - A_{i-101}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-101} - A_{i-102}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-102} - A_{i-103}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-103} - A_{i-104}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-104} - A_{i-105}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-105} - A_{i-106}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-106} - A_{i-107}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-107} - A_{i-108}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-108} - A_{i-109}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-109} - A_{i-110}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-110} - A_{i-111}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-111} - A_{i-112}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-112} - A_{i-113}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-113} - A_{i-114}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-114} - A_{i-115}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-115} - A_{i-116}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-116} - A_{i-117}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-117} - A_{i-118}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-118} - A_{i-119}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-119} - A_{i-120}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-120} - A_{i-121}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-121} - A_{i-122}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-122} - A_{i-123}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-123} - A_{i-124}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-124} - A_{i-125}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-125} - A_{i-126}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-126} - A_{i-127}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-127} - A_{i-128}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-128} - A_{i-129}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-129} - A_{i-130}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-130} - A_{i-131}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-131} - A_{i-132}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-132} - A_{i-133}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-133} - A_{i-134}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-134} - A_{i-135}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-135} - A_{i-136}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-136} - A_{i-137}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-137} - A_{i-138}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-138} - A_{i-139}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-139} - A_{i-140}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-140} - A_{i-141}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-141} - A_{i-142}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-142} - A_{i-143}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-143} - A_{i-144}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-144} - A_{i-145}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-145} - A_{i-146}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-146} - A_{i-147}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-147} - A_{i-148}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-148} - A_{i-149}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-149} - A_{i-150}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-150} - A_{i-151}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-151} - A_{i-152}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-152} - A_{i-153}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-153} - A_{i-154}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-154} - A_{i-155}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-155} - A_{i-156}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-156} - A_{i-157}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-157} - A_{i-158}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-158} - A_{i-159}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-159} - A_{i-160}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-160} - A_{i-161}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-161} - A_{i-162}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-162} - A_{i-163}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-163} - A_{i-164}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-164} - A_{i-165}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-165} - A_{i-166}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-166} - A_{i-167}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-167} - A_{i-168}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-168} - A_{i-169}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-169} - A_{i-170}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-170} - A_{i-171}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-171} - A_{i-172}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-172} - A_{i-173}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-173} - A_{i-174}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-174} - A_{i-175}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-175} - A_{i-176}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-176} - A_{i-177}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-177} - A_{i-178}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-178} - A_{i-179}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-179} - A_{i-180}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-180} - A_{i-181}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-181} - A_{i-182}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-182} - A_{i-183}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-183} - A_{i-184}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-184} - A_{i-185}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-185} - A_{i-186}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-186} - A_{i-187}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-187} - A_{i-188}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-188} - A_{i-189}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-189} - A_{i-190}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-190} - A_{i-191}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-191} - A_{i-192}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-192} - A_{i-193}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-193} - A_{i-194}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-194} - A_{i-195}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-195} - A_{i-196}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-196} - A_{i-197}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-197} - A_{i-198}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-198} - A_{i-199}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-199} - A_{i-200}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-200} - A_{i-201}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-201} - A_{i-202}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-202} - A_{i-203}) / B_{i-1/2} + \frac{(z_{bi+1} - z_{bi}) + (h_{i+1} - h_i)}{(A_{i-203} - A_{i-204}) / B_{i-1/2} + \frac{(z_{bi+$$

ある水面形の経時変化も示している。これより、推定結果は、(1)平均的な河床形状の実測値を再現していること、(2)流量については、時間平均するとCaseS-DI, T, F, DIIの実測流量をそれぞれ2.5%, 1.0%, 2.7%, 0.4%程度の誤差で再現できること、(3)粗度係数については、時間平均するとCaseS-DI, T, F, DIIのエネルギー勾配に基づく実測値をそれぞれ2.8%, 1.0%, 3.0%, 0.6%程度の誤差で再現できること、などが確認できる。図-4に、無次元掃流力 τ_* と無次元有効掃流力 τ'_* 、流速係数 $\phi(=u/u_*)$ の時空間平均値の推定結果と実測値との比較を示す。なお、図中には、各小規模河床形態の岸・黒木の式⁶⁾に基づく関係も併せて示している。これより、無次元掃流力と無次元有効掃流力の関係は、CaseS-DIで若干の差異はあるものの、岸・黒木の式との関係に沿っており、各小規模河床形態の変化による無次元掃流力と無次元有効掃流力の関係や抵抗特性の変化を再現していることが確認できる。図-5に、流砂量の推定結果と実測値との比較を示す。これより、推定結果は、(1)流砂量がCaseS-F, DII, T, DIの順で大きくなること、(2)時間平均するとCaseS-DI, T, F, DIIの実測値をそれぞれ102.8%, 102.5%, 5.0%, 39.6%程度の誤差で再現できること、などが確認できる。図-6に、岸・黒木の式⁶⁾の無次元有効掃流力とKovacs and Parker式²⁾の流砂量、流砂量の推定結果と実測値との比較を示す。これより、推定結果は、(1)CaseS-Tについては流砂量の実測値が流砂量式よりも小さく、遷移領域での式(6)の適用性が低いこと、(2)CaseS-DIIについてはCaseS-Tに比べ、式(6)の適用性は高いこと、などが確認できる。流砂量が無次元有効掃流力の1.5乗で求められることを踏まえると、CaseS-DI, T, F, DIIの無次元有効掃流力の推定結果と実測値との間には、それぞれ60.2%, 60.1%, 3.4%, 24.9%程度の差が生じたと考えられる。

4. おわりに

本研究から、本推定法は、局所的な河床位や粗度係数や流砂量の再現性には課題が残るものの、小規模河床形態発生時の平均的な河床位と流量、粗度係数を再現できることが確認された。このように、本推定法は、水面形の情報から、小規模河床形態発生時の抵抗やその時の流砂量の推定に有用なツールであると考えられる。

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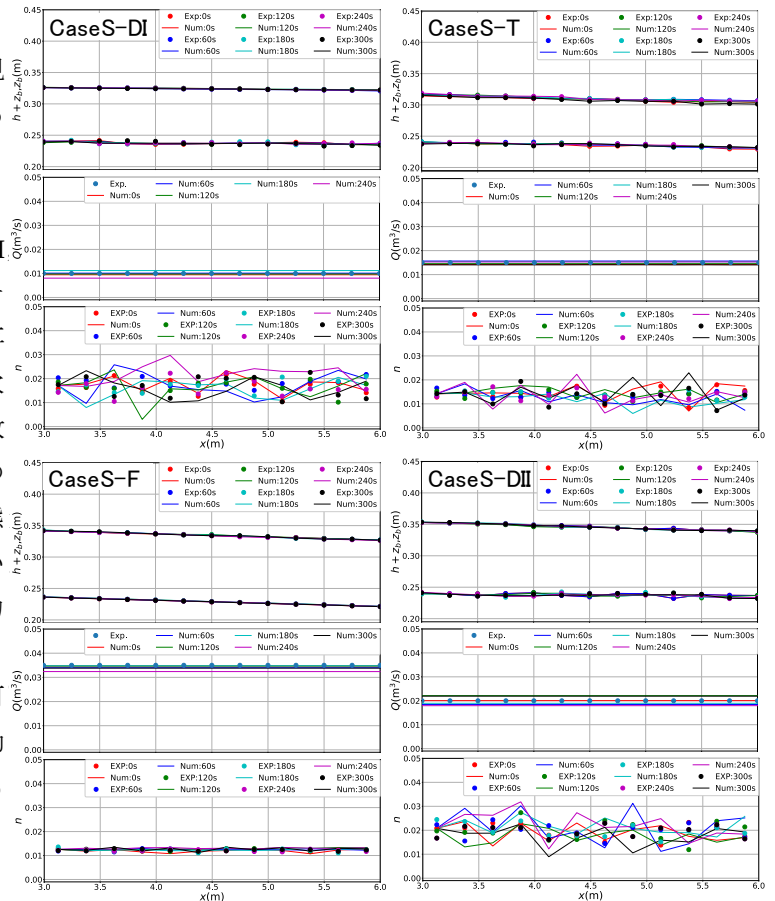


図-3 河床位、流量、粗度係数の推定結果と実測値との比較

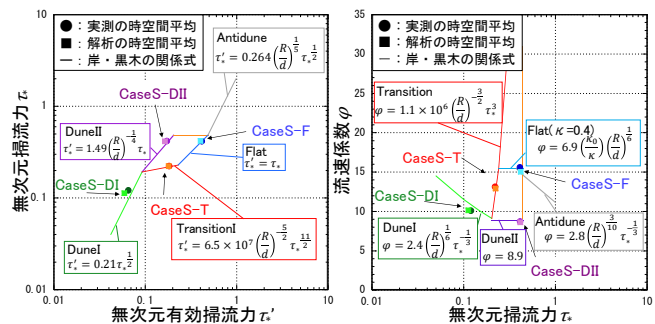


図-4 無次元掃流力と無次元有効掃流力、流速係数の関係

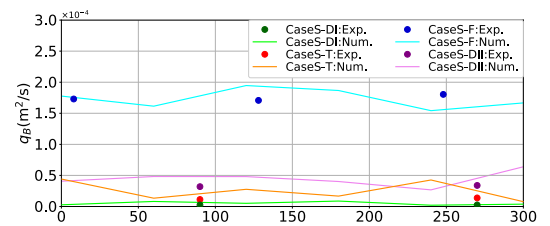


図-5 下流端流砂量の推定結果と実測値との関係

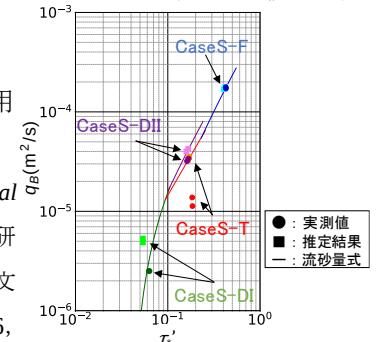


図-6 流砂量式との比較